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# Development of a new adaptive comfort model for low income housing in the central-south of chile

A. Pérez-Fargallo [a], J.A. Pulido-Arcas [a], C. Rubio-Bellido [b,*], M. Trebilcock [c], B. Piderit [b], S. Attia [d]

[a] Department of Building Science. University of Bio-Bio, Chile
[b] Department of Building Construction II. University of Seville, Spain
[c] Department of Architectural Design. University of Bio-Bio, Chile
[d] Sustainable Building Design Lab, Dept. UEE, Applied Sciences, Université de Liège, Belgium

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ABSTRACT

Adaptive comfort plays an important role in defining comfort standards when considering comfort in buildings in free-running mode, including adaptation to external temperatures, opening windows and changing clothing. In this regard, two international standards provide the fundamental basis to model the necessary equations: EN 16798 (formerly 15251) and ASHRAE 55–2017. This research intends on assessing the feasibility of applying these standards to the Chilean context, where a legal framework has begun to be implemented to regulate the occupant's comfort in social housing. Extensive monitoring of inhabitants in existing units under free-running mode has been undertaken in several social housing projects in the city of Concepción (Chile) and the collected data has been contrasted against the international standards. Results show that users in these houses show more tolerance to cold temperatures, thus, despite being allocated below the standards' lower limits, they are considered to be in thermal comfort. As a result, the outcomes of this research can shed light on the feasibility of applying international standards to social housing and low-income families in Chile. The study presents a proposal for a novel adaptive comfort model for Chile. The new model proposes adapting the thermal comfort threshold's lower limit in order to develop a national standard that better reflects the inhabitants' needs and socio-economic culture. The study demonstrates how the proposed model best fits the thermal comfort conditions in social housing in Chile.



## 1. Introduction

The building sector is currently facing numerous challenges, amongst which containing energy consumption, eradicating fuel poverty and mitigating the effect of climate change appear as the most prevalent [1]. According to diverse sources, building energy consumption ranges between 30% and 40% of the world's total [2] and this is showing an upward trend when looking towards the future, with the possibility of increasing to 38.4 PWh in 2040 [3]. In this sense, building energy consumption and energy consumption per capita are no longer reliable indicators of economic prosperity and social welfare [4]. In order to quantify energy consumption within a building, several factors have to be considered at the same time in order to address thermal comfort requirements: location, envelope features, internal loads, and HVAC equipment [5]. The energy consumption or indoor temperature of a given space under certain loads can be established by considering thermal comfort standards; therefore, it remains crucial to properly define those standards in order to achieve comfort for users while reducing energy consumption [6]. Nowadays, building energy performance indicators are associated with primary energy source consumption, $CO_2$ emissions or net energy distribution, which together determine, energy efficiency. The EN 15603:2008 and EN 52003–1:2007 standards [7,8] are based on quantifiable parameters associated to the energy consumption. Their evaluations are based on set point temperatures and hours of operation. However, those fixed temperatures are not suitable for simulations of buildings inhabited or occupied by low income users, such as social housing

*Abbreviations:* ASHRAE, american society of heating, refrigerating, and air-conditioning engineers; BRE, british research establishment; CO2, carbon dioxide; ECSV, sustainable construction standard for housing; GDEEVS, design guide for energy efficiency in social dwellings; HVAC, heating, ventilation and air conditioning; MINVU, Chilean ministry of housing and town planning; OGUC, general ordinance on urban [planning and building construction; RITCH, Chilean standard for heating, ventilation, air conditioning and refrigeration; SCAT, smart control and thermal comfort; TC, technical committee.

* Corresponding author.
*E-mail address:* carlosrubio@us.es (C. Rubio-Bellido).

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[9] or public premises such as primary schools [10]; these studies rely on the fact that the performance of these structures should be assessed on the basis of a free running or mixed mode operation in extreme cold or warm conditions.

In this context, Chile is making strides towards implementing a regulatory framework in the field of thermal comfort, especially adaptive thermal comfort. This framework considers the user's capability to be within adaptive comfort ranges along with the time when dwellings do not need HVAC systems, as an indicator of thermal comfort. This study, continuing along this line, aims at establishing the basis for a newly developed adaptive comfort standard for Chile, one which can be used to define new benchmarks for thermal comfort in social dwellings promoted by the Chilean MINVU.

This goal is clarified by a series of surveys applied to residents of social dwellings located in the Chile's central Bio-Bio region. Residents were asked about their thermal sensation, while actual external and internal temperatures were measured. Those results will be contrasted against those provided by the European Standard, EN 16798 (formerly 15251) and ASHRAE 55–2017. The outcomes of this research clarify how these international standards can be applied to a given national context, providing not just researchers, but also policymakers, with procedures to adapt these standards to a variety of legal frameworks. It is expected that the results from this research will help set up the basis for a future Chilean standard on adaptive thermal comfort that, in turn, may be applied to better assess energy consumption for dwellings promoted by the Chilean government.

The paper is organized in six sections. Firstly, the background of the Chilean policy regarding thermal comfort on social dwellings is provided. Secondly, the basis of the adaptive comfort models that have been taken into consideration are discussed. Thirdly, results of the survey are described and summarized. The fourth section describes how the results from the survey have been contrasted with the international standards. In the fifth section, the interpretation of this comparison provides an adapted equation that better describes the behaviour of low income Chilean residents in social dwellings in order to achieve comfort. Finally, the main conclusions and implications of the results obtained are clarified.

## 2. Literature review

### *2.1. International adaptive thermal comfort models*

ASHRAE, from the first attempts in 1995, sponsored a field survey project (RP-884) aimed at analysing data from existing buildings [11]. This approach has been kept in the latest edition of ASHRAE 55–2017 [12]. In the EU context, some initiatives have been already undertaken to address this phenomenon. The adaptive comfort model considered in EN 16798 (formerly 15251) has been developed from the SCATs project (Smart Control and Thermal Comfort), establishing information of naturally ventilated buildings and their occupants [6,13,14]. The application of these two models is suitable for buildings that are mainly used for human occupation with sedentary activities, buildings with easy access to operable windows and where occupants can adapt their clothing to indoor thermal oscillation from 0.5 to 1.0 clo [15]. With regard to the occupants' physical activity, these activities must be pretty sedentary, with metabolic activity levels between 1.0 and 1.3 met [16]. The starting point for our discussion is that outdoor temperature was proven to have the most influence on indoor comfort conditions; therefore, a mathematical relation between external temperatures and indoor temperatures seems suitable to define this comfort model [17–20]. This approach fits that one made by Humphreys, who suggested that comfort temperature $T_c$ can be calculated for free running buildings using the following equation [21]:

$$T_c = aT_{OUT} + b \tag{1}$$

where $T_c$ is the comfort temperature (°C), $T_{OUT}$ is the outside temperature index (°C) and $a$ and $b$ are constants. Humphreys indicates that monthly outside temperature can be used to calculate the indoor comfort temperature index. Based on that point, a variety of studies have attempted to clarify the mathematical expression that would best reflect the comfort temperatures according to the behaviour of users in naturally ventilated or hybrid buildings. There is a general tendency to adapt international adaptive comfort standards to a specific context, regarding the limitations and the applicability of using the adaptive model for residential buildings around the world. Attia & Carlucci compiled the most relevant ones up to 2015 [5] and an update of that compilation is presented here (Table 1), focusing specifically on developing and transition economies with a similar socioeconomic context to Chile. These research projects basically rely on the same conceptual framework: Comfort temperatures for users inside not fully air-conditioned buildings are defined by the external temperatures from the preceding days, with an exception that applies when external temperatures are extremely high or low. While, it has been proven that the thermal adaptability of these users depends on a variety of factors, such as their socioeconomic level or their expectations regarding their dwellings. As Chile does not have yet a standard for adaptive thermal comfort, let alone one for social dwellings, this research is intended to propose an adaptive comfort model for low income residents of social dwellings in a concrete region of Chile to help clarify the following questions. First, what the minimum thermal comfort conditions that those residents have are; secondly, how to establish a new thermal comfort benchmark that can serve as a basis to improve these conditions in the future.

### *2.2. Chilean context*

#### *2.2.1. Social housing*

With regard to Chile, it has to be said that this country has a long tradition of social housing, a policy which has been used continuously since 1936 [35]. As a general view, the number of built units grew steadily from 1936 to the 1984–1996 period, where around 110,000 dwelling units were produced in 12 years. In the nineties and the beginning of the 21st Century these figures dropped, but they have been rising again since 2005. As for the data of 2014, it is estimated that Chile has around 344,402 subsidized housing units, 26,043 of which are located in the Bio-Bio region. Social housing in Chile is heavily influenced by pre-fabricated prototypes for apartments and residential complexes. These have a faster construction, cheaper building costs and tabulated technical solutions. There are a variety of prototypes, ranging from single dwellings to blocks, which connect dwellings using 8 basic grouping systems [35]. These subsidized housing programs have provided the most vulnerable Chilean households with basic housing with minimal technical standards.

#### *2.2.2. Thermal comfort framework*

Chile, with regard to how thermal comfort is treated in this social housing plan, is moving from a construction-based approach, based on the concept of transmittance and thermal envelope, to a user approach, based on the concepts of thermal comfort. This is despite adaptive thermal comfort still not being implemented in the regulatory framework. In fact, energy efficiency in buildings was not even regulated before 2006. At the moment, the only mandatory building standard is the General Ordinance on Urban Planning and Building Construction [36] (OGUC using its Spanish acronym). This code was enacted in 1992 and was later amended in 2006 to include limit values regarding the transmittance of

**Table 1**
Adaptive comfort models.

| Source | $a$ | $f(T_{ext})$ | $b$ | Range of applicability |
|---|---|---|---|---|
| [14] | 0.33[a] | Exponentially weighted running mean outdoor air temperature | 18.8[a] | $f(T_{ext})\in[10, 30]$°C Upper limit<br>$f(T_{ext})\in[15, 30]$°C Lower limit |
| [22] | 0.31[a] | Exponentially weighted running mean outdoor air temperature | 17.8[a] | $f(T_{ext})\in[10, 33.5]$°C |
| [20] | 0.315[c]<br>0.34[a] | Exponentially weighted running mean outdoor air temperature | 17.82[c]<br>17.63[a] | $f(T_{ext})\in[5, 30]$°C |
| [17] | 0.302[a] | Exponentially weighted running mean outdoor air temperature | 19.39[a] | $f(T_{ext}) > 10$°C |
| [23] | 0.54[a] | Monthly mean outdoor air temperature | 13.5[a] | $f(T_{ext})\in[10, 30]$°C |
| [24] | 0.36[c] | Historical monthly mean outdoor temperature | 18.5[c] | $f(T_{ext})\in[5, 35]$°C |
| [25] | 0.255[a]<br>0.04[b] | Monthly mean outdoor effective temperature (ET[a]) | 18.9[a]<br>22.6[b] | $f(T_{ext})\in[5, 32]$°C |
| [26] | 0.38[b] | Monthly mean outdoor air temperature of the previous month | 17.0[b] | $f(T_{ext})\in(5, 35)$°C |
| [27] | 0.534[b] | Exponentially weighted running mean outdoor air temperature | 12.9[b] | Not defined |
| [11] | 0.31[a] | Running mean of the preceding fortnight | 17.6[a] | Not defined |
| [28] | 0.534[a] | Monthly mean outdoor air temperature | 11.9[a] | Not defined |
| [29] | 0.57[a] | Daily mean outdoor air temperature (°C), i.e., the 24 h arithmetic mean for the day in question. | 13.8[a] | $f(T_{ext})\in[19.4, 30.5]$°C |
| [30] | 0.26[c] | Prevailing mean outdoor temperature | 16.75 | $f(T_{ext})\in[8,27]$°C |
| [31] | 0.4711[c] | Monthly mean outdoor air temp. of the previous month | 13.273 | $f(T_{ext})\in[10,35]$°C |
| [31] | 0.6596[c] | Monthly mean outdoor air temp. of the previous month | 7.6006 | $f(T_{ext})\in[16,35]$°C |
| [31] | 0.7479[c] | Monthly mean outdoor air temp. of the previous month | 5.8434 | $f(T_{ext})\in[-2,35]$°C |
| [31] | 0.7394[c] | Monthly mean outdoor air temp. of the previous month | 6.2652 | $f(T_{ext})\in 10.35]$°C |
| [31] | 0.6232[c] | Monthly mean outdoor air temp. of the previous month | 8.5217 | $f(T_{ext})\in[13,30]$°C |
| [32] | 0.56[a] | RM outdoor temperature with 0.45 as the time constant $\alpha$ | 12.6 | $f(T_{ext})\in[12.5,31]$°C |
| [33] | 0.28[c] | RM outdoor temperature with 0.45 as the time constant $\alpha$ | 17.87 | $f(T_{ext})\in[13,38]$°C |
| [34] | 0.24 [c] | Exponentially weighted running mean outdoor air temperature | 19.3 | Not defined |

[a] Model exclusively developed for free running and naturally ventilated buildings.
[b] Model exclusively developed for air-conditioned buildings.
[c] Model developed for all types of buildings (free running, mixed mode, air-conditioned).

thermal envelope, dividing Chile into climate-dependent thermal zones. Several non-mandatory documents were published, looking to establish a better regulatory framework to better control energy consumption of buildings while creating proper thermal comfort standards. The RITCH (Chilean standard for heating, ventilation, air conditioning and refrigeration) [37] is a standard that establishes fixed setpoints for both operative temperature and relative humidity: 23–25°C and 40–60% in summer; 20–22°C and 40–60% in winter. Much more recently, in August 2017, a new standard related to the procedures to calculate cooling and heating was enacted [38], although it has not yet come into force. In 2009, the non-mandatory *Design Guide for Energy Efficiency in Social Dwellings* (GDEEVS in its Spanish acronym) [39] included a basic guideline on thermal comfort and updated reference values for limit transmittances included in the OGUC. Adaptive comfort was first mentioned in a Chilean technical standard in 2012, in the *Standardized reference guidebook on energy efficiency and thermal comfort parameters, according to geographical areas and building typologies, with application in tender processes of the public bureau of architecture* (TDRe by its Spanish acronym) [40]. This established new standards for hygrothermal comfort, making a distinction between "artificially conditioned buildings" and "passive buildings". Regarding the first group, fixed set points are considered for both heating and cooling; for the second group it considers one of the adaptive comfort equations mentioned by Szokolay on behalf of Auliciems [41], who developed a suitable model for both air-conditioned and free running buildings.

$$T_n = 17.6 + 0.31 \cdot T_m \tag{2}$$

where $T_n$ is the neutral indoor air temperature and $T_m$ is the mean monthly outdoor air temperature, with the model being valid for $T_n$ between 18°C and 28°C. Here, temperatures should be between $T_{inf} = T_n$-2.5°C and $T_{sup} = T_n + 2.5$°C, 95% of the time while the building is being used; however, by expanding this limit to $T_{inf} + -1$°C and $T_{sup} + 1$°C, they should fit 98% of the time. It also updates the restriction on limit transmittances for all climates in Chile. In summary, the Chilean regulatory framework seems capable to dealing with comfort, and more specifically adaptive comfort, but a clear framework has still not been implemented.

## 3. Methodology

The methodological framework of this research initially included documented work and field work to find a statistically representative sample of social dwellings in the Bio-Bio region. Once a sample was gathered, selected dwellings were monitored for both internal and external conditions. Surveys about thermal comfort were also delivered to the residents of these dwellings. All the data collected was then processed statistically with two goals: First, to find out whether the ASHRAE-55 and EN 16798 (formerly 15251) standards would represent these conditions and second, to try to find a mathematical model, that is, a comfort model, that would better represent this case-study.

### *3.1. Case selection*

The Chilean Government, from 1964 to 2015, has delivered 3,671,646 subsidies for social dwellings, accounting for a total of USD $19 billion since 1990 [42]. During this time span, a variety of dwellings, including single houses, detached houses, terraced houses and apartment blocks have been delivered; a single unit usually features a usable area of 33–55 m$^2$. Given this panorama, the target group was chosen on a basis of being dwellings that benefited from any type of government subsidy, or in other words, social dwellings. All types were included in the survey, which comprised 6 single dwellings, 6 terraced houses, 25 detached houses and 3 apartments located in condominiums, giving a total of 40 dwellings.

### *3.2. Monitoring*

Monitoring was initially carried out, taking into account specific characteristics of the Bio-Bio region's climate. This region's climate is classified as Csb (following the Koppen–Geiger classification, it corresponds to a temperate climate with dry and warm

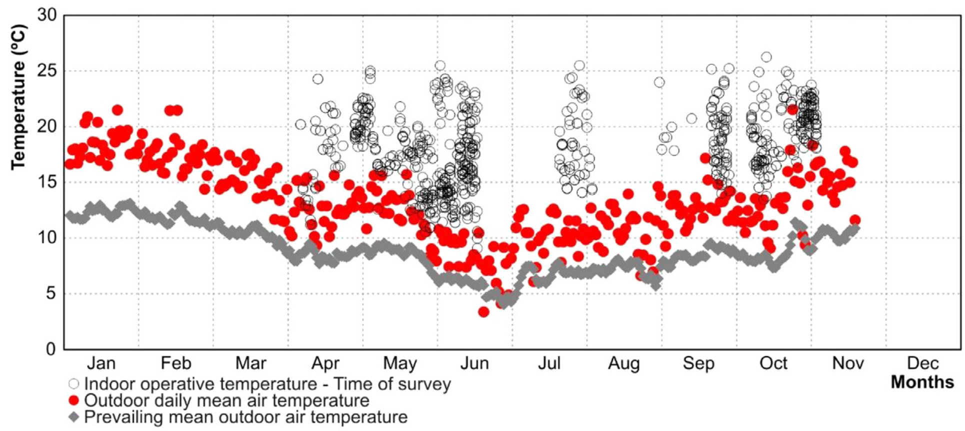


**Fig. 1.** Prevailing mean outdoor air temperature and daily mean temperature and indoor operative temperature at the moment of survey.

**Table 2**
Characteristics of the monitoring device.

| Probe | Sensor type | Measuring range | Resolution | Accuracy |
|---|---|---|---|---|
| Dry bulb temperature (Ta) | Pt100 | −40 a 100°C | 0.1°C | ±0.1°C |
| Globe temperature (Tg) (globe therm Ø150 mm) | Pt100 | −10 a 100°C | 0.1°C | ±0.1°C |
| Relative humidity (RH) | Capacitive sensor | 5–98% | 0.1% | ±2% |
| Air velocity (Va) | NTC 10kΩ | 0.05 a 5 m/s | 0.01 m/s | ±0.05 m/s (0–1 m/s)<br>±0.15 m/s (1–5 m/s) |

summers). The temperatures in the warmest month mean do not reach 22°C and the coldest month average above 0°C. This climate suggests that, at first sight, that no discomfort conditions should be expected from warm weather.

Monitoring of outdoor temperatures was done for 11 months in the area of Concepción, from January to the end of November 2016. While, the dwellings were monitored over 7 months, during the coldest period of the year, comprising autumn, winter and the beginning of spring. This monitoring period was chosen considering the local climate. Although research on thermal comfort in Chile is very scarce in nature, in the few studies there are about thermal comfort, particularly in Chilean primary schools, these found discomfort only for cold conditions [10,43].

The dwellings were monitored during the coldest months so that information about the resident's comfort demand could be gathered when the average outdoor daily mean temperature was below 15°C and 10°C (Fig. 1, in the Section 4.1). These figures were established using the lower limits set by the EN 16798 (formerly 15251) and ASHRAE standards. In the former this sets the lower limit below which the three thermal comfort categories are constant. Thus adaptive comfort is not applicable [14]. In a similar fashion, in the latter, ASHRAE 55–2017 establishes that both the upper and lower limit for thermal comfort for acceptability levels of both 80% and 90% should be constant and, therefore. adaptive comfort is not valid [12].

Data collection was made using a weather station for the outdoor temperatures (Vantage Pro 2) and a measuring cell model Delta Ohm HD 32.3 for indoors, which records the dry bulb temperature (Ta), globe temperature (Tg), relative humidity (HR), and air speed (Va) at 5 min intervals. The technical features of the monitoring device are summarised in Table 2; the equipment was installed in the living room of the dwellings, at a height of 1.1 m from the ground so that it would not interfere with the residents' daily routine [44].

*3.3. Surveys*

Residents from the dwellings considered were surveyed over 7 months (April–October 2016) the coldest period (Fig. 1, in Section 4.1). 121 people between 14 and 84 were surveyed repeatedly (according to the monitoring); 57 of them were men and 64 women. A total of 709 surveys were made (roughly 3 people per household). Regarding data collection, four types of dwellings were used, two of them were aimed at gathering data about the dwelling, and the remaining two about the residents themselves. The first pair was made once and the residents had to provide information about their dwellings and how they used them; the second pair was delivered once a day for a week, period in which the indoor thermal conditions of the dwellings were also being monitored. The pair of surveys about thermal comfort was based on standardized methods [12,45]. In the first part of the survey, the users were asked to inform about their clothing, their activity and where the survey was being answered. After that, they had to score about their Thermal Sensation Vote (TSV), Thermal Preference Vote (TPV), their personal tolerance, affective assessment and their Thermal Acceptability (TA) according to the following sections (Table 3). As they are inhabiting their own dwellings, users are prone to regulating thermal comfort by a variety of measures: The residents were surveyed about two of them: Level of clothing and degree of physical activity. Regarding the first one, they could tick multiple options from a list of clothes and later on their level of clothing in CLO was calculated; regarding the second one, they could choose only one option from a list and later on their level of physical activity in MET was estimated-.

Each participant was provided with seven questionnaires, one for each day. The date and time were included when they filled these in. Residents were also instructed to fill in the questionnaire as close as possible to the monitoring cell, but avoiding any interaction with it. In total 709 questionnaires were collected, 52 of which were discarded, giving a final number of 657 valid question-

**Table 3**
Types of questions, answers, variables and range of data.

| Type of question | Type of answer | Variable | Range |
|---|---|---|---|
| Using the following list, please check the type of clothes you are wearing at this moment | Residents can choose from a list of clothes. Multiple options are allowed. | CLO | 0.26–1.87 |
| Choose your position and level of physical activity at this moment | Residents can choose from a list of positions and physical activities. Only one option is allowed | MET | 0.8–2 |
| What sensation do you feel at this moment? | Cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (1) warm (2), hot (3)" | TSV | −3– +3 |
| At this moment you would like to feel... | Much colder (−3), cooler (−2), slightly colder (−1), the same (0), slightly warmer (1), warmer, much hotter" | TPV | −3– +3 |
| Using a scale from 1 to 5 with 1 being acceptable and 5 unacceptable, in your opinion the temperature of the house at this moment is..., | Numerical scale from 1 to 5, with 1 being acceptable and 5 unacceptable | Personal tolerance | 1–5 |
| Affective assessment; "You find the room temperature... | Pleasant, unpleasant, very unpleasant, unbearable" | Affective assess-ment | No range |
| Taking only into account your personal preferences. How would you consider the thermal environment of the house at this moment? | Generally acceptable or generally unacceptable. | TA | No range |

naires; an average of 17.72 per household. All of them were filled in between 6am and midnight, except two of them, which were filled in at 1:20 and 3:00am.

### 3.4. Statistical treatment

The collected data were processed to organize and clarify the information using the following procedure. First, amongst the 709 surveys, 25 were found to be inconsistent, with a $TSV+TPV \leq 3$ or $> 3$ [46]. Considering the operative temperatures and the TSV for each survey, comfort temperatures could be calculated using Griffithséquation [47]:

$$T_{comf} = T_{op} - \frac{TSV}{b} \tag{3}$$

where Top is the operative temperature, TSV the Thermal Sensation Vote and b = 0.5 the Griffiths constant [48]. This author proposed a value of b = 0.33 to be used in studies about adaptive comfort [49], but Dear & Brager, after examining ASHRAE RP-884′s research project database, found 0.5 as a more accurate value, due to the relation between the TSV and the globe temperature [25]. Regarding the SCATs Project, Nicol and Humphreys also found 0.5 as an adequate value when dealing with adaptive comfort models [48]. For these reasons, the value of 0.5 will be used in this analysis and will be compared against the results of this study.

The resulting comfort temperatures were arranged correspondingly with outdoor running mean temperatures to study the outliers. Box and whiskers plots were used to analyze the median value and the interquartile range; 26 outliers that were outside this range were detected and eliminated. For the calculation of the prevailing mean outdoor air temperature $\theta_{rm}$ of a particular day, outside average temperatures of the previous 7 days are used, with $\theta_{ed-1}$ being the daily outdoor average temperature of the previous day; $\Theta_{ed\text{-}2}$ the daily outdoor average temperature two days before, and so on and so forth; this is summarized up in Eq. 4 [14].

$$\theta_{rm} = (\theta_{ed-1} + 0.8{*}\theta_{ed-2} + 0.6{*}\theta_{ed-3} + 0.5{*}\theta_{ed-4} + 0.4{*}\theta_{ed-5} + 0.3{*}\theta_{ed-6} + 0.2{*}\theta_{ed-7})/3,8 \tag{4}$$

657 out of the 683 comfort temperatures were used in the analysis, eliminating 26 outliers that could lead to a bias in the results. These user comfort temperatures were assessed using the ASHRAE 55–2017 and EN 16798 (formerly 15251):2008 standards [12,14], along with all the monitored temperatures in the dwellings. Jointly, the deviation between the users' thermal sensation and the users' thermal preference were calculated as follows. TSV and TPV were arranged as percentages, with regard to the difference between the neutral temperature of the model as a function of $\Theta_{rm}$ and the operative temperature of the room; each pair of data was considered at the moment when the survey was being filled in by the user. In this way, TSV labelled as "Slightly warm", "Neutral" and "Slightly cool" were considered as comfort levels; in the same fashion, TPV labelled as "Slightly cooler", "The same" and "Slightly warmer" were considered as no change (The same).

Finally, the comfort temperatures obtained from the surveys and the monitored data were compared using a regression analysis to clarify which temperature difference, with regard to the model's neutral temperature, could be considered to achieve 80% thermal acceptability according to the TSV. Finally, the operative temperatures that were previously monitored in the dwellings were assessed on the basis of the aforementioned model, which was created using the surveys' results.

## 4. Results

### 4.1. Results regarding discomfort conditions

During the measurement period (Fig. 1), outdoor daily mean air temperature ranged between 5°C and 15°C, most of the time sitting around 10°C. As a result, the prevailing mean outdoor temperature, which considers the 7 previous days prior to the study period, was found to be below 10°C. The lower comfort limit for thermal acceptability according to the EN 16798 (formerly 15251) model is established at 15°C, while following the ASHRAE model this is 10°C. Hence, during the period considered, both models would be outside the acceptability range. These conditions are found during 7 months of the year, so that could lead us to think that the standardized comfort models are not applicable for this climate. However, according to the monitoring and the TSV from the surveys, it was found out that the user's comfort temperature ranged between 10°C and 26°C. Active conditioning devices are not always used in these dwellings, leading to some margin for the user's thermal adaptability.

At the same time as the monitoring was being done, surveys about the users' thermal perception (TSV), thermal preference (TPV) and tolerance were carried out, quantifying the levels of acceptance and thermal sensation (Fig. 2). During the monitoring and the surveys, the users' thermal perception was mainly neutral (45.1%), with being slightly cool the second option (29%); cool and slightly warm scored 11.3% and 10.8% respectively. Extreme perceptions, namely, warm (2.1%) and cold (1.7%) appeared in a few isolated cases, and no one reported being hot in any case. This data shows that, in global terms, the thermal perception of the users ranges between slightly cool and slightly warm, accounting

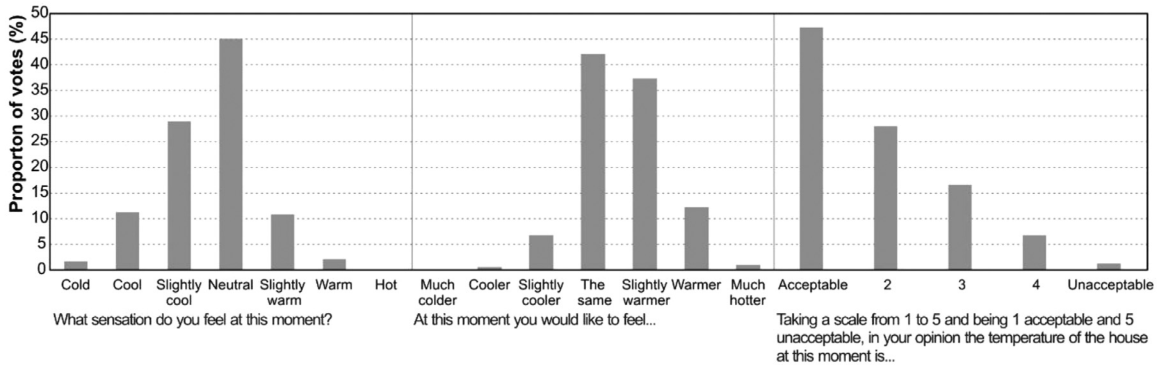


**Fig. 2.** Proportion of votes about perception, preference and tolerance of indoor temperature.

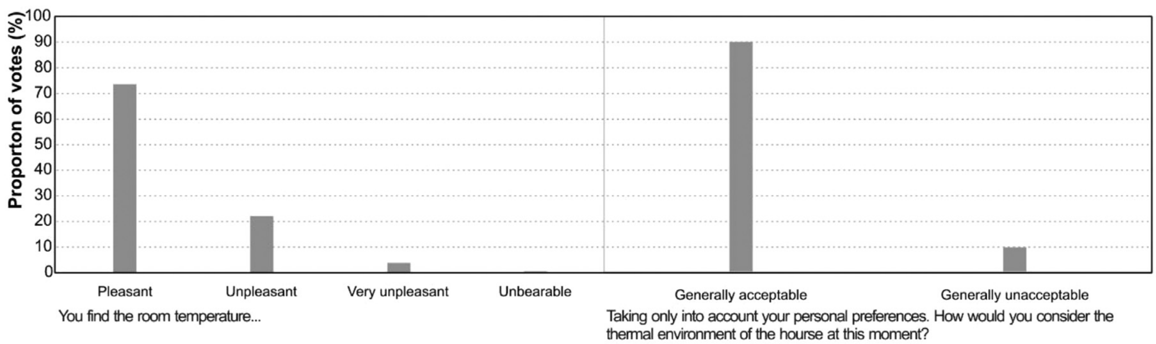


**Fig. 3.** Proportion of votes about evaluation and acceptability of indoor temperature.

for 84.9% of the cases when the user comfort temperature was calculated between 10°C and 26°C.

This data extracted from the TSV and TPV surveys matches the ones from tolerance, assessed on a scale from 1 to 5, with 1 being acceptable and 5 unacceptable. 47.3% of the cases considered the indoor temperature of the dwelling as being acceptable; the more unacceptable the sensation is, the lower the score; 2 (28.0%), 3 (16.6%), 4 (6.8%) and 5 (1.3%). Adding up the percentages corresponding to 1 and 2, it can be concluded that 75.4% of the users were found to be within an acceptable environment. That poses the following question: Even being outside the scope of application for adaptive comfort standards and with active conditioning systems not always being in operation (Fig. 2), a high percentage of the residents who answered, felt comfortable tolerating a little cold; besides, they considered that with only a slight increase in temperature, the thermal environment would improve further.

Two more questions were included in the survey to have a higher accuracy in the evaluation of the indoor temperature's acceptability (Fig. 3). A high percentage of those answering, evaluated the room temperature as pleasant (73.7%); while those who considered it unpleasant accounted for 22.1% of the total, only 3.8% of them found it unpleasant and an insignificant 0.4% found it unbearable. On a simpler scale, 90.1% of residents found the thermal environment generally acceptable and only 9.9% considered it generally unacceptable.

*4.2. Application of ASHRAE 55–2017 comfort model to the results*

The neutral temperature ($T_n$) of the ASHRAE 55–2017 model can be calculated using Eq. 5 and can be applied if the prevailing mean outdoor temperature is greater than 10°C and less than 33.5°C. Temperature ranges for 80% and 90% of thermal acceptability are set as ± 3.5°C (7°C) and ± 2.5°C (5°C) from neutral temperature (Eq. 5). For outside the range of 10°C–33.5°C, the prevailing mean outdoor temperature along with the upper and lower limits become constant both for 80% and 90% thermal acceptability.

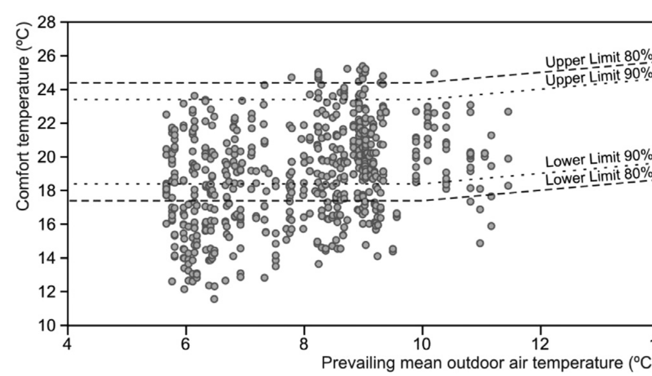


**Fig. 4.** Scatter plot: Comfort temperature and prevailing mean outdoor air temperature within the 80% and 90% ASHRAE 55–2017 limits.

$$T_n = 0.31 \cdot \theta_{rm} + 17.8 \quad (5)$$

Results from the relationship between the prevailing mean outdoor temperature and the comfort temperature have been cross-checked against the neutral along with the 80% and 90% acceptability range from ASHRAE 55–2017 (Fig. 4). Very few points of the scatter plot fall within the acceptability range of the ASHRAE (the limit in the x axis is 10°C), with most of them being between 6°C and 9°C. For those prevailing mean outdoor temperature values, comfort temperatures fall between 12°C and 25°C approximately.

Fig. 5, in order to clarify to what extent the TSV and the TPV obtained from the surveys match the results that would be expected if the ASHRAE standard were applied in the concrete case, shows two identical graphs for TSV and TPV. In both of them, the percentage of votes corresponding to a given TSV is plotted against

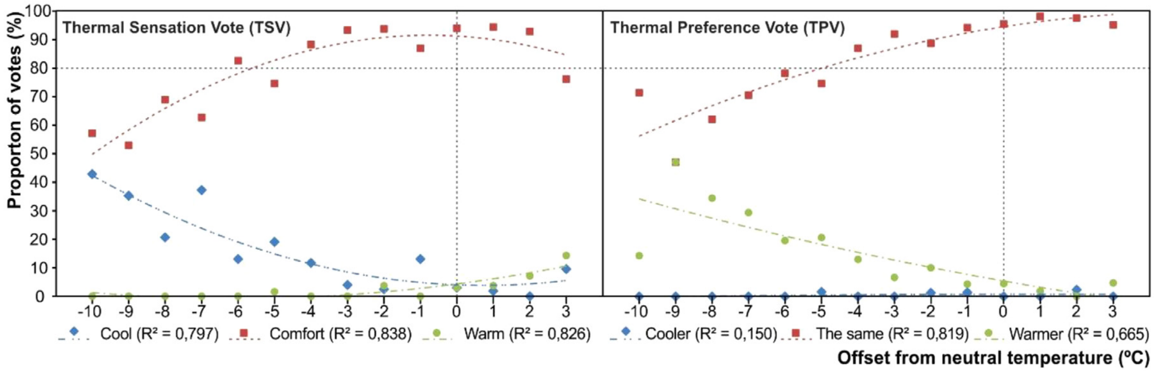


**Fig. 5.** Proportion of thermal sensation votes and thermal preference votes from offset neutral temperature determined according to ASHRAE 55–2017.

the deviation from the neutral temperature using the ASHRAE standard. These votes are divided into comfort, cool and warm (TSV) and comfort, cooler and warmer (TPV). For instance, when we look at the TSV graph, we find that when the temperature inside the house falls 10°C below the neutral temperature from the ASHRAE model, around 55% of users felt comfortable and around 45% felt cool. As a result, the following tendencies have been identified. At first, the TSV comfort votes range between 52.9% and 94.4% of the total; this pattern is reproduced in the TPV, ranging between 60% and 98.1% of the total. Secondly, the percentage of votes that feel the indoor environment as cool, ranges between 0% and 42.9%; those who prefer a warmer environment accounts for 0% to 47.1%. Thirdly, a very low proportion of votes consider the environment as warm (< 15%) and there is virtually no preference for cooling down the environment. This data is relevant, as there is a deviation from the neutral temperature that ranges between −10°C and + 3°C.

Regression curves have also been included to identify the most representative offset from the ASHRAE neutral temperature, also including the horizontal line that represents the limit for 80% of the proportion of votes (Fig. 5). Only the regression curves for comfort (TSV) and the same (TPV) surpass this upper limit. In the case of TSV, this means that a high percentage of those answering find themselves in comfort when temperatures are between −5.61 C below and + 4.10°C above the ASHRAE neutral temperature; the amplitude is 9.70°C, which implies an increase of 2.70°C above the ± 3.5 °C (7°C) from ASHRAE 55–2017. The maximum of the regression curve has been found at −0.75°C below ($R^2 = 0.838$), which indicates that users are significantly more tolerant to cold conditions than those in the evaluated model. The same can be seen regarding the TPV. The percentage of residents who answered that they would prefer to be "the same" falls below 80% only when indoor temperature is displaced 5°C below the ASHRAE standard, which implies a deviation from this model.

### *4.3. Application of EN 16798 (formerly 15251) comfort models to the results*

The EN 16798 (formerly 15251) establishes four comfort ranges as per the expectations, as well as other factors that influence comfort perception and building age.

It also establishes the applicability of the lower limit from a range of the outdoor running mean temperature as 15°C– 30°C, as well as the upper limit of 10°C–30°C. When outside these limits, comfort is considered static or dependent on different equations (Table 4), pursuant the standard (Table 3). The model's neutral temperature ($T_n$) can be calculated using Eq. 6.

$$T_n = 0.33 \cdot \theta_{rm} + 18.8 \quad (6)$$

**Table 4**
Statistical analysis for the proposed comfort model.

| Range of applicability | Equation | Descriptive statistics | | |
|---|---|---|---|---|
| | | SE | MAE | *P* value |
| $\theta_{rm} > 6.5$°C | $T_n = 0.678{*}\theta_{rm} + 13.602$ | 2.71 | 2.16 | 0.000 |
| 5°C ≤ $\theta_{rm}$ ≤ 6.5°C | $T_n = 0.115{*}\theta_{rm} + 17.075$ | 2.91 | 2.31 | 0.675 |

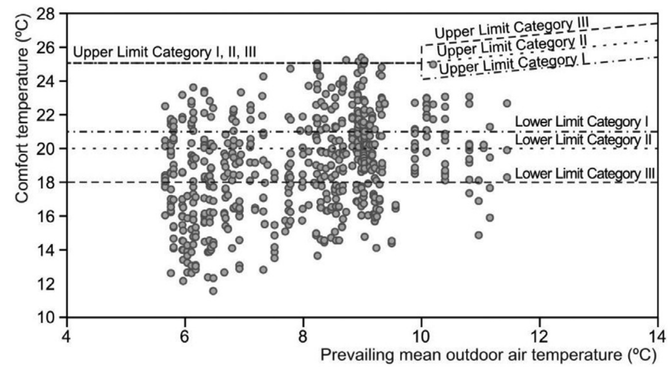


**Fig. 6.** Scatter plot: User comfort temperature and outdoor running mean temperature within the limits of categories I, II and III as per EN 16798 (formerly 15251).

The same analysis has been made with regard to the EN 16798 (formerly 15251) standard, in this case representing the outdoor running mean temperature considering the three categories of the standard (I, II and III) (Fig. 6). None of the points are within the limits of applicability of this standard (lower limit of 15°C), which are, indeed, stricter than those from ASHRAE 55–2017.

The relation between the percentage of TSV and TPV votes on one hand, and the offset from neutral temperature according to the EN 16798 (formerly 15251) standard (Fig. 7), reveals similar tendencies to the ASHRAE 55–2017. The TSV comfort vote ranges between 55.9% and 97.4%. While the 80% limit is surpassed only by the votes corresponding to comfort, and, as a consequence, the neutral temperature is displaced between −6.06°C and + 3.42°C with respect to the reference from EN 16798 (formerly 15251). The 90% limit is displaced by between −3.39°C and + 0.75°C. Hence, their amplitudes are 9.48°C and 4.14°C, respectively. That implies a wider range of 3.48°C for 80% acceptability compared to Category II (± 3.0°C) (Table 3). For 90% acceptability, the amplitude is similar, increasing 0.14°C with regard to Category I (± 2.0°C) (Table 3). The regression curve's maximum is found at around −1.32°C ($R^2 = 0.840$), so in this case, the displacement is slightly wider; increasing 0.57°C with regard to ASHRAE. The same is seen regarding the TPV; the percentage of residents who answered that they would prefer to be "the same" falls below 80% only when

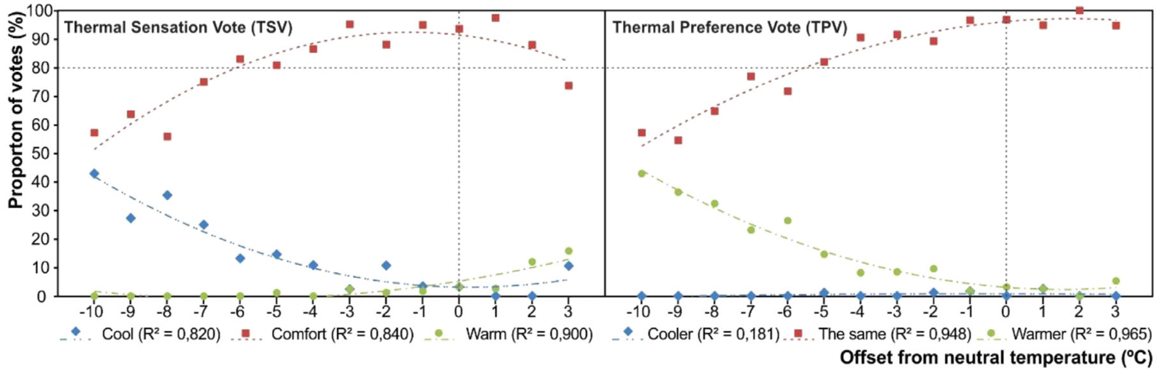


**Fig. 7.** Proportion of thermal sensation vote and thermal preference vote from offset from the neutral temperature determined using EN 16798 (formerly 15251).

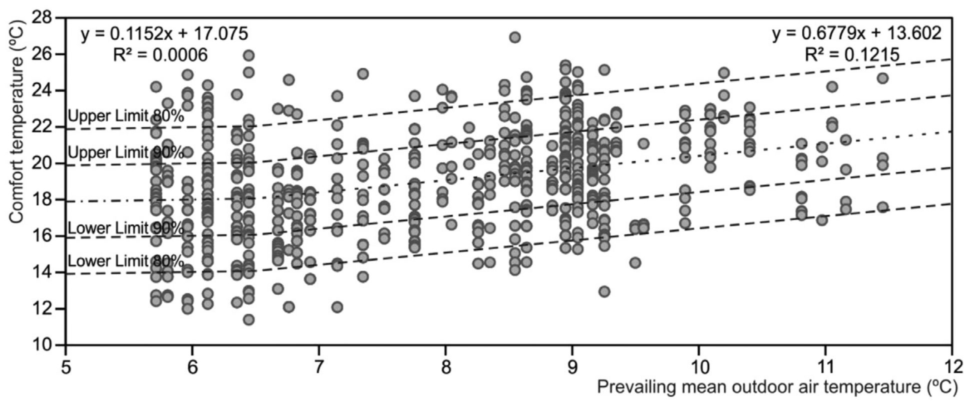


**Fig. 8.** Scatter plot: User comfort temperature and prevailing mean outdoor air temperature within a range ± 4°C using user comfort temperature regressions obtained.

indoor temperature is displaced 5.5°C below the EN 16798 (formerly 15251) standard, which implies a deviation of + 0.5°C from the ASHRAE model.

### *4.4. Adaptive comfort model derived from the survey results and monitoring process*

As shown in previous sections (Figs 4 and 6), most of the points fall outside the range of applicability both for the ASHRAE 55–2017 and EN 16798 (formerly 15251) standards. While, both TSVs and TPVs have maximum values (Figs 5 and 7) that do not match those predicted by these standards. For this reason, additional statistical analysis has been made to clarify the neutral temperature as a function of the prevailing mean outdoor temperature (Fig. 8). According to the data, two trends can be identified. First, when the prevailing mean outdoor temperature is above 6.5°C, ($\theta_{rm}$) > 6.5°C, the neutral temperature ($T_n$) is defined by the following Eq. (7), with $R^2 = 0.1215$:

$$\theta_{rm} > 6.5^{\circ}C: \ T_n = 0.678 * \theta_{rm} + 13.602 \quad (7)$$

Second, when the prevailing mean outdoor temperature falls below 6.5 °C and is above 5°C, 5°C $\leq \theta_{rm} \leq$ 6.5°C, the equation changes and the line is practically horizontal (8):

$$5^{\circ}C \leq \theta_{rm} \leq 6.5^{\circ}C: \ T_n = 0.115 * \theta_{rm} + 17.075 \quad (8)$$

Descriptive statistics for the proposed equations are depicted in Table 4; Standard error (SE), mean absolute error (MAE) and *P* values are shown; the threshold for confidence level has been stablished at 95%. *P* values for the equation that represents neutral temperature for prevailing mean outdoor temperatures over 6.5°C is null, which indicates a strong correlation between variables; *P* value for the other equation suggest that correlation is weaker, and that can be explained by the fact that the line is practically horizontal, being neutral temperature independent from external temperatures.

Fig. 9 which represents the proportion of TSV and TPV with regard to the offset from neutral temperature, is the same as Figs 5 and 7. Notwithstanding this, on this occasion, the proportion of thermal votes has been checked against the newly proposed model. The percentage of TSV that accounts for more than 80% of the total is found for temperatures that are −4.217°C below and + 4.368°C above the neutral temperature calculated. The acceptability range in this case is 8.586°C, some 2.586°C wider than EN 16798 (formerly 15251) Category II and 1.586°C wider than ASHRAE's 80% acceptability. If a 90% acceptability is considered, the limits are −2.531°C and 2.683°C, with their amplitude being 5.214°C. In this case, it is 1.214°C wider than EN 16798 (formerly 15251) Category I and 0.214°C wider than ASHRAE's 90% acceptability. The limits for 65% acceptability are −5.913°C and 6.064°C, with an amplitude of 11.978°C. This is 3.978°C wider than EN 16798 (formerly 15251) Category III (±4°C). With this amplitude, the calculated neutral temperature is 17.075°C for a prevailing mean outdoor temperature of 5°C, with the lower limit being 11.162°C. This temperature is very low to be considered as "comfortable", despite the fact that EN 16798 (formerly 15251) considers 65% acceptability.

The curve that is intended to represent comfort conditions ($R^2 = 0.912$) has its maximum value right by the 0 value for TSV. This means that it matches thermal neutrality (in fact, the difference is only 0.075°C with respect to neutrality). This fact, together with the symmetry of the curve with respect to the neutral temperature, suggests that this model more accurately represents the actual thermal sensation of the occupants than the international models. With regard to TPV at 80% acceptability, the lower offset of the operative temperature is −3.613°C with regard to the neutral temperature calculated. The TPV curve ($R^2 = 0.829$) has a

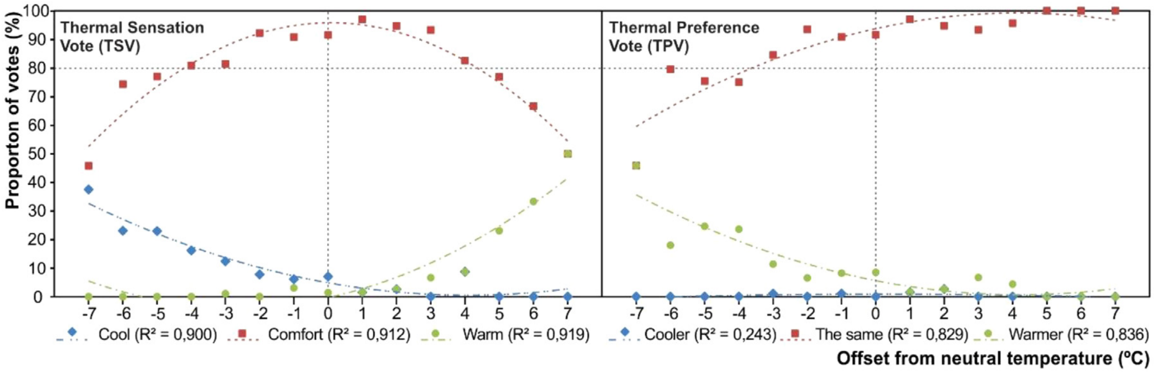


**Fig. 9.** Proportion of thermal sensation vote and thermal preference vote from offset from the neutral temperature determined following the new developed model.

**Table 5**
Comfort temperature ranges in regard to prevailing mean outdoor air temperature ($\Theta_{rm}$) of the proposed model.

| | | Prevailing mean outdoor air temperature $\Theta_{rm}$ - Comfort temperature | | |
|---|---|---|---|---|
| Acceptability | Limit | $0°C \le \theta_{rm} < 5°C$ | $5°C \le \theta_{rm} \le 6.5°C$ | $6.5°C < \theta_{rm} \le 12°C$ |
| 90% (±2.5°C) | Upper comfort limit | 20.25 | $0.115*\theta_{rm} + 19.67$ | $0.678*\theta_{rm} + 16.01$ |
| | Lower comfort limit | 15.25 | $0.115*\theta_{rm} + 14.67$ | $0.678*\theta_{rm} + 11.01$ |
| 80% (±4°C) | Upper comfort limit | 21.75 | $0.115*\theta_{rm} + 21.17$ | $0.678*\theta_{rm} + 17.51$ |
| | Lower comfort limit | 13.75 | $0.115*\theta_{rm} + 13.17$ | $0.678*\theta_{rm} + 9,51$ |

maximum near 100% when the offset from neutral temperature is approximately + 4°C. The following can be interpreted, looking at the data from TPS and TSV together (Fig. 9). People who consider themselves in comfort according to TSV represent 80% or more of the surveyed sample when temperatures are, offset, roughly, by −4°C and + 4°C from the neutral temperature; while, people who would not prefer any change in their temperature according to TSV reach a maximum near 100% of the surveyed residents when temperature is offset by + 4°C from the neutral temperature, and fall below 80% when this temperature is −4°C (exactly −3.61°C) from neutral temperature. This implies that, there is a range of approximately ± 4°C from neutral temperature that would satisfy at least 80% of the residents.

The 80% and 90% acceptability limits have been carried out to calculate the lower and upper limits of thermal comfort for the TSV (Fig. 9). The 65% limit, considered in the EN 16798 (formerly 15251) involves lower indoor temperatures (< 12°C), which are more closely related to TPV preference for warmer conditions. Hence, this limit is not considered in the proposed model. The upper limit is established at + 4.368°C and the lower limit at −4.217°C regarding the 80% thermal acceptability; + 2.682°C and −2.531°C have been established for 90%. Taking these into account, and in order to surpass 80% and 90%, an acceptability limit of ± 4°C (> 80%) and ± 2.5°C (> 90%) is considered. Neutral temperature from under 5°C to approximately 0°C, without considering prevailing mean outdoor temperatures that are too low, can be considered constant at 17.075°C. Table 5 depicts the final form of the proposed adaptive comfort model.

### 4.5. Accuracy of the new proposed model

Finally, the newly proposed model has been compared against the other two standards to clarify its accuracy when representing actual thermal comfort (Fig. 10). The indoor operative temperature for each one of the 40 dwellings was checked against the prevailing mean outdoor temperature, using the three models. The analysis is based on the adjustment of the limits of these standards as a function of the percentage of time when each model falls within each category.

The proposed model scores better than ASHRAE 55–2017 and EN 16798 (formerly 15251) regarding 80% and 90% acceptability; much better in the case of the latter. Both standards have virtually no percentage of time over the upper limit; the proposed standard demonstrates a small percentage of time when this situation appears. The percentage of time when each model falls under the lower limit is variable, but in this case the two standards show a more balanced situation; however, the proposed model improves these figures.

To sum up, the proposed model derived from the survey shows a more balanced distribution of the percentages for each situation with regard to thermal comfort, which means that the underlying mathematical expression more accurately represents the actual situation that was observed in the surveyed social dwellings.

## 5. Discussion

Chile is on its way towards establishing a regulatory framework to balance thermal comfort and energy efficiency. In this study, we propose different comfort categories based on long term thermal monitoring and user-centred comfort surveys. We considered the adaptability of occupants living in social housing as a potential scenario to reduce energy consumption. We aim to establish the basis for a new adaptive comfort standard for Chile. In this regard, the following discussion will elaborate on the study's findings, discuss its strengths and limitations and the implications of our research along with future perspectives.

### 5.1. Summary of main findings

Since 2006, Chile has been slowly starting to implement a regulatory framework related to energy efficiency in buildings, and it is our belief that this path should inexcusably include a declaration related to the indoor environment. Therefore, the development of a comfort model requires understanding the importance of the several variables that control comfort in free running operation during cold or warm conditions. This study is based on long-term thermal monitoring coupled to thermal sensation and preference votes for 121 residents who inhabit social dwellings located in the Bio-

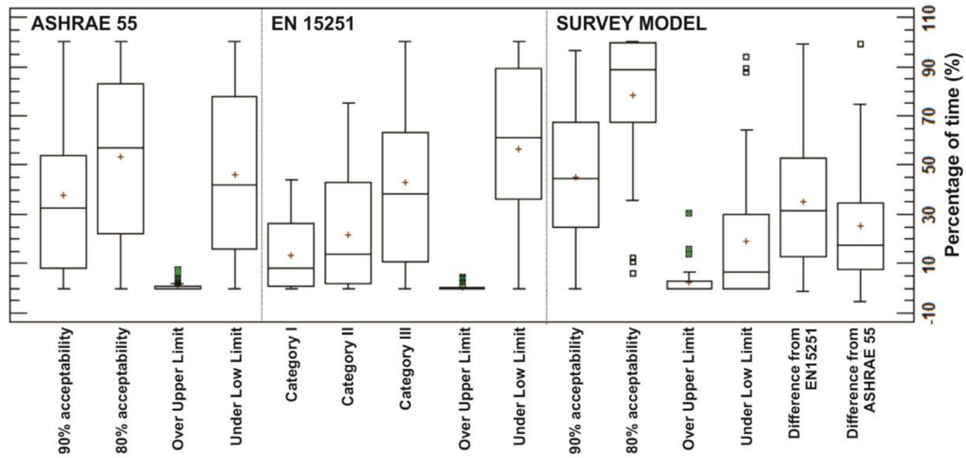


**Fig. 10.** Percentage of time during which each dwelling fell into different thermal comfort categories. Comparison between ASHRAE 55–2017, EN 16798 (formerly 15251) and the model devised from the user's answers.

Bío Region, which is representative of the climate of Central-South Chile. The main findings of the study are listed below:

- People who inhabit social housing consider themselves comfortable with very low indoor temperatures that can reach 14°C.
- Based on monitoring and self-reported surveys, indoor temperatures range from the lowest value of 12°C to the highest value of 26°C, when the prevailing mean outdoor temperatures range from 5.5°C to 11.5°C. According to the statistical analysis, the authors have defined two categories for thermal comfort that are applicable to social housing in the Bío-Bío region:
  - 90% acceptability provides a basic adaptive comfort limit ranging from 14.58°C to 24.24°C
  - 80% acceptability provides an improved adaptive comfort limit ranging from 13.08°C to 25.74°C.
- Tolerating low temperatures does not mean inhabitants are comfortable. However, other influencing factors like fuel poverty and cultural adaptation (clothing, food, personalised heating systems, central use of spaces) also exerts an influence on this phenomenon. Therefore, taking this research as a starting point, the authors recommend that 13°C should be considered as the lowest tolerable limit during winter. Thus, the thermal balance of the proposed comfort model is calibrated through to 13°C.
- The authors, based on our study's findings, recommend the implementation in the forthcoming Chilean regulations of the categories as a new benchmark for thermal comfort in social dwellings. This can be the first step towards guaranteeing a minimum comfort level in social housing and setting an attainable benchmark for the building industry, so that construction technology can be adapted. The monitoring-based thermal comfort model can promote informed decision-making not only for energy efficient housing, but also for a healthy and comfortable indoor environment.
- We recommend revising this lower threshold every five years considering the socio-economic conditions and the state of affairs in the building industry.

### 5.2. Relation with existing research

This study has discovered that low-income residents consider themselves in comfort at much lower temperatures than comfort standards usually state. This behaviour is common for low-income residents and users of buildings in different contexts.

In the Chilean context, the limited studies that can be found suggest that, for primary school students [43][10], comfort temperatures are also lower than those considered as standard: In winter, comfort temperatures ranged between 14 and 15°C, depending on the estimation method. In the international context, more references can be found that match those findings pointed out by this study. Residents in traditional Nepalese houses found themselves to be in thermal comfort with temperatures as low as 13 and 16°C [50]. Another study conducted in the region of Gifu in Japan found out that, during winter, comfort temperatures ranged from 12°C to 16°C, depending on the operation of windows [51]. Another study focusing on economically deprived families living in Cyprus found a relationship between the average family income and the indoor temperature inside homes during winter; the most deprived group showed temperatures between 12 and 15°C, though residents declared not being comfortable [52]. Another large-scale study conducted in different climate zones of China also found a similar tendency [31]: Indoor temperatures inside homes during the cold season were found to be around 16 and 18°C in some climates, below usual comfort standards.

In this way, the results from this research match those from other studies conducted. Although the mathematical expression and the lower thermal comfort limits during the cold season may be different, a similar pattern can be observed. Low income residents find difficulties in keeping their homes warm, so they adapt to colder conditions and, as a result, lower their expectations with regard to thermal comfort. Usual standards for thermal comfort cannot adequately represent this behaviour. Therefore, newly adapted models become necessary to explain this phenomenon and establish a starting point to increase thermal comfort standards for those residents in the future.

### 5.3. Limitations of the study

The model presents some limitations.

The first one is related to the sample size. This research relies on 657 thermal comfort votes of low-income residents of social dwellings, which is smaller than usual studies on thermal comfort. As the most paradigmatic example, we can quote the study by De Dear et al conducted worldwide [11] with a total of 20,693 votes. However, when breaking down the results into concrete countries and climates, sample sizes are similar, or even smaller, than the one present in this study. Besides, other studies, which also focus on very concrete target groups, rely on a smaller body of data: 338 votes for evaluating thermal comfort of students in India [53], 115 votes for evaluating thermal comfort of office workers in Bogota (Colombia) [54] or 1258 votes for evaluating thermal comfort in four different climates of Mexico [55], giving around 315 votes for each climate. This research is also focused on a very concrete target group and is intended to be a starting point to pave out the way for further research on this matter; therefore, despite the body of data not being as big as those in wide-scope studies, it is similar to other studies with specific target groups. The results are also consistent, and that indicates that the study is, up until now, heading on the right path; future research encompassing a wider body of data will allow checking this model and improving it further.

The monitoring included the coldest period of the year and, consequently, gathering more thermal votes would also lead to a longer monitoring period, which would also include the summer period. As stated before, and according to the few studies about thermal comfort in central-south Chile, thermal discomfort is not expected to be associated with warm conditions. Anyway, that would have to be assessed by future research itself.

This research did not take into account air quality, which is a controversial issue in this country. Air pollution in major Chilean cities like Santiago [56] and main urban areas in Central-South Chile [57] represents a public health problem and exerts an influence on the recurrence of respiratory illnesses in children [58]. The high prices of centralised energy (electricity and gas) in the country, along with abundantly available wood, results in a high dependence on the latter. As a result, 46.6% of the energy used in Chilean homes comes from wood, 21.4% from LPG, 17.6% from electricity, 10.1% from natural gas and 3.3% from paraffin [59]. This high dependence on wood implies poor indoor air quality.

The authors are aware that indoor environmental quality should not be only focused on thermal comfort but should embrace other issues, with one of the most crucial being indoor air quality. Thus, we are aware about the limitation of our study of not coupling the temperature thresholds to air quality. For example, MINVU is proposing in the new version of the Housing Thermal Performance Standard in 2018, to couple the envelope's thermal resistance to the risk of poor indoor air quality. We would therefore like, to address air quality in the future research work.

Statistical analysis for the proposed model has found a strong correlation between indoor comfort conditions and external conditions for outside temperatures over 6.5°C; however, for outside temperatures under 6.5°C and over 5°C this correlation seems weaker. However, we should consider that, in accordance with the findings from other researches, indoor comfort conditions become independent from external conditions for very low temperatures; this model also supports this fact. Anyway, future improvement of this model will focus also on this concrete issue.

Another issue that was intensively investigated as part of this study, is the determination of the 13°C lower comfort limit. Despite the monitoring results and self-reported surveys indicating the acceptance of 13°C by most of the investigated occupants, we should not overlook the correlation to fuel poverty that is directly related with the poor thermal expectancies of those residents. We are convinced that 13°C is a tolerable limit during winter, but 17°C should be the lowest reasonable limit during winter for a national standard.

However, starting with 17°C would imply achieving higher thermal resistance of the building envelope, which is economically and technically very challenging at the moment. So, the suggestion is made to start with 13°C as the lowest reasonable limit during winter as a starting point, that is until the market and the technological development can reach this standard and stricter limits can be put into practice.

### *5.4. Implications for practice and future research*

This research has direct implications on guiding the construction industry and building regulations policies in Chile. By determining minimum comfort limits for social housing, we empower housing occupants. At the same time, we allow building upon the comfort assumptions and developing passive design and construction solutions and technologies. More importantly, the study can help to set a cornerstone for indoor environmental quality that comprises 1) operative temperatures, 2) air quality, 3) humidity control and 4) ventilation. Thus, the future research should build on our comfort model thresholds and establish minimum construction requirements and practices.

With the future improvement of socio-economic conditions and construction quality and practices in the Bío-Bío Region, we expect local authorities would revise the comfort model every five years. Comfort is an economic and cultural issue and requires being articulated through building standards that are continuously updated.

## 6. Conclusions

This research has established a new adaptive thermal comfort model which is applicable to social housing located in Central-South Chile, featuring a cold climate. This model is applicable when current standards, such as ASHRAE 55–2017 and EN 16798 (formerly 15251), are not able to adequately represent the behaviour, thermal preferences and thermal expectations of low income residents. In short, this model aims at better reflecting the tendency of these users to adapt to outdoor conditions, when artificial conditioning systems are hardly used due to their economic limitations.

This fact opens up the debate about the relationship between thermal adaptability, fuel poverty and a variety of factors that exert an influence on the prediction of comfort, mainly in social dwellings. 40 cases and 121 residents were monitored and surveyed over 7 months in the cold season, 709 surveys were collected and data about TSV and TPV was compiled. The conclusions indicate that, although the basic structure proposed for the assessment of thermal comfort in the international standards, ASHRAE 55–2017 and EN 16798 (formerly 15251), remains valid, (that is, the range of indoor comfort temperature is a function of the prevailing mean outdoor temperature only over a threshold lower value), the threshold values must be recalculated on the basis of the target group. This means that there is a deviation in the thermal comfort sensation for the users considered and, as a consequence, the proposed model better reflects the economic and social reality of the surveyed residents. The model reflects, in this way, the current situation regarding thermal comfort, but the research also proposes higher benchmarks that should be attained in the near future; that is, thermal comfort should advance from a basic threshold of 13°C to stricter values.

The conclusions also point out that there is a possibility of this model being replicated in other socioeconomic contexts. This means that, in a country with a variety of climates just like Chile, standards should embrace those singularities. Moreover, the continuous updates in building codes and construction technology should bring the resulting improvements in indoor conditions in social dwellings, which will require new surveys in the future. The replication of this methodology will bring periodic updates of the proposed adaptive thermal comfort models for social housing in the Bío-Bío region, adapting the model to the current socioeconomic and cultural context.

## Conflicts of interest

The authors declare no conflict of interest.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.enbuild.2018.08.030.

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